Probing the Galactic cosmic ray flux with submillimeter and gamma ray data

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Abstract.
The study of Galactic diffuse γ radiation combined with the knowledge of the distribution of the molecular hydrogen in the Galaxy offers a unique tool to probe the cosmic ray flux in the Galaxy. A methodology to study the level of the cosmic ray "sea" and to unveil target-accelerator systems in the Galaxy, which makes use of the data from the high resolution survey of the Galactic molecular clouds performed with the NANTEN telescope and of the data from γ-ray instruments, has been developed. Some predictions concerning the level of the cosmic ray "sea" and the γ-ray emission close to cosmic ray sources for instruments such as Fermi and Cherenkov Telescope Array are presented.

Keywords: Cosmic ray origin; Molecular Clouds; Gamma rays
PACS: 98.38.Dq,98.38.Mz,8.70.Sa,98.70.Rz

INTRODUCTION

Cosmic rays (CRs) up to at least 10^{15} eV are believed to be emitted by Galactic sources, such as supernova remnants, but no conclusive evidence of the acceleration has been found yet. A trace of ongoing cosmic ray acceleration is the γ-ray emission produced by these highly energetic particles when they scatter off the interstellar medium gas, mainly atomic, molecular and ionised hydrogen. In fact, from the hadronic collisions neutral pions emerge and in turn they decay into two γs. For this reason γ-ray astronomy has always played a key role to probe the Galactic cosmic ray flux and to solve the longstanding question of the origin of cosmic rays. Whereas the atomic hydrogen is uniformly distributed in the Galaxy, the molecular hydrogen is usually aggregated in dense clouds, and the γ-ray emission from such clouds is particularly intense. A multi-frequency approach which combines the data from the upcoming and future γ-ray missions with the data from the submillimeter and millimeter surveys of the molecular hydrogen is therefore crucial to probe the Galactic cosmic ray flux.

In the following a methodology to make predictions of the level of the cosmic ray "sea" and to unveil target-accelerator systems in the Galaxy by using the data from the NANTEN survey from a region in Galactic longitude $340^o < l < 350^o$ and Galactic latitude $-5^o < b < 5^o$ will be described. In particular, one can put upper limits on the CR "sea" based on the observations of the dense environments in the Galaxy. If the flux from certain clouds is below the predictions based on the locally measured CR density, this implies that the "sea level" is currently overestimated.

THE NANTEN SURVEY

Equipped with a 4 m submillimeter telescope, the NANTEN instrument surveyed the southern sky in the molecular hydrogen, by using the J=1-0 line of CO at 115.271 GHz (2.6 mm). The angular resolution of this survey is equal to 4 arc-min and the mass sensitivity is about 100 solar masses at the Galactic Centre at 8.5 kpc [1, 2, 3]. Following [4, 5] a three dimensional map of the molecular hydrogen density is obtained by assuming a flat rotation curve model of the Galaxy with uniform velocity equal to 220km/s. The factor $X = 1.4 \times 10^{20}\, e^{(R/11\,\mathrm{kpc})}\,\mathrm{cm^{-2}K^{-1}km^{-1}s}$, where R is distance from the Galactic Centre, is used to translate the CO integrated intensity into H_2 column density.

MOLECULAR CLOUDS AS TRACERS OF COSMIC RAYS

Passive molecular clouds

Cosmic rays diffuse in the Galactic magnetic fields for timescales of the order of 10^7 years before escaping the Galaxy. During these timescales the particles accelerated by individual sources mix together, lose memory of their origin, and contribute to the bulk of Galactic cos-

mic rays known as the cosmic ray "sea". Because of the diffusion process, the injection spectra from individual sources, which according to the diffusive shock acceleration theory are expected to have a power-law slope close to -2, get softened. The cosmic ray flux measured close to the Earth, with its characteristic soft -2.7 spectrum, is usually assumed to be representative of the average cosmic ray flux throughout the Galaxy. However, the spectral feature of the γ-ray emission detected by HESS from the Galactic Centre region [6], and EGRET observations of the Orion nebula [7] suggest that the CR density varies within the Galaxy.

In order to test the assumption that the local CR flux is representative of the level of the cosmic ray "sea", we investigate the emissivity of molecular clouds located far away from candidates cosmic ray sources. These molecular clouds, illuminated by the average cosmic ray density and thus denominated "passive" molecular clouds, can be used as cosmic ray barometers. The detection of a single passive cloud which emits a lower γ-ray flux than that expected assuming the local cosmic ray flux would provide evidence that the cosmic ray flux locally measured is not representative of the average cosmic ray flux. In Figure 1 and 2, respectively, the longitude and latitude profiles of the γ-ray emission from the Galactic region $340^{\circ} < l < 350^{\circ}$ and $-5^{\circ} < b < 5^{\circ}$ due to the proton flux measured at Earth are plotted. There is a clear peak in the emission at about 346° along the Galactic Plane, next to a dip. Since the proton flux in the whole region is assumed to be constant, the peak in the γ emission must be due to an enhancement of the gas density somewhere along the line of sight from the direction 346° longitude and 0° latitude. Statistically speaking such an enhancement of the gas density from this direction can be due to a single or at most few very dense molecular clouds. In Figure 3 the gas density as a function of the line of sight distance from the longitude 346° on the Galactic Plane is shown. The gas density is particularly high only within 0.5 and 2 kpc distance, where it amounts to about $9\,\mathrm{cm}^{-3}$, and thus the peak in the γ emission in Figure 1 is mostly due to the cosmic ray flux within 0.5 and 2 kpc distance from the Sun. Notably, for such densities no question about the CR penetrability within the cloud arises. The γ-ray flux from such region, which Fermi would detect above 1 GeV is $2 \times 10^{-8}\,\mathrm{photons}/(\mathrm{cm}^2\mathrm{s})$, and for Cherenkov Telescope Array (CTA) above 100 GeV is about $1 \times 10^{-11}\,\mathrm{photons}/(\mathrm{cm}^2\mathrm{s})$, which for observing a 1 degree extended region is close to the sensitivity of the detector. In this way the cosmic ray flux at 346° longitude on the Galactic Plane at a distance within 0.5 and 2 kpc can be estimated, and upper limits can be put on the CR "sea". If the flux from these clouds is below the predictions based on the locally measured CR density, this implies that the "sea level" is currently overestimated [8].

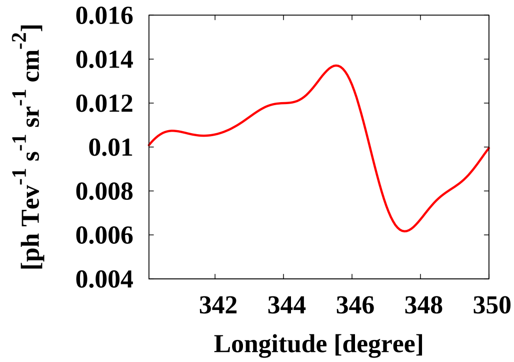

FIGURE 1. The longitude profile of the γ-ray emission at 1 GeV which would be measured by Fermi from the region $340^{\circ} < l < 350^{\circ}$, integrated over the latitude range $-5^{\circ} < b < 5^{\circ}$, if the cosmic ray flux is equal to the flux measured close to the Earth.

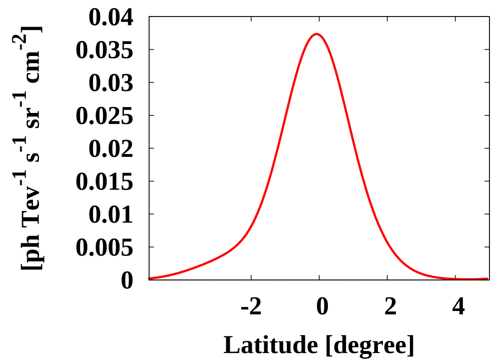

FIGURE 2. The latitude profile of the γ-ray emission at 1 GeV which would be measured by Fermi from the region $-5^{\circ} < b < 5^{\circ}$, integrated over the longitude range $340^{\circ} < l < 350^{\circ}$, if the cosmic ray flux is equal to the flux measured close to the Earth.

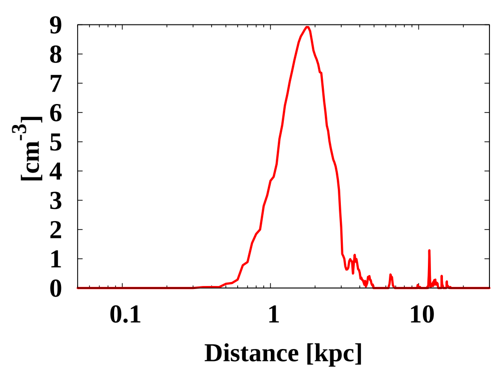

FIGURE 3. The gas density as a function of the line of sight distance from the direction 346° on the Galactic Plane is shown.

Active molecular clouds

Cosmic ray sources are believed to accelerate hadrons and heavier nuclei up to at least the so called "knee" at about 10^{15} eV. The direct observation of cosmic rays from these candidate injection sites is not possible since CRs diffuse into the Galactic magnetic fields, and the contributions from individual sources merge into the "sea" of background cosmic rays, losing the information on the original acceleration locations and spectra. However, before diffusing into the magnetic fields, the newly injected cosmic rays scatter off the local gas and produce γ-ray emission through pion decay, which can significantly differ from the the diffuse emission contributed by the "sea" CRs because of the hardness of the young spectrum, not yet steepened by diffusion [9, 10]. The extension of such diffuse sources does not generally exceed a few hundred parsecs, the scale at which the spectra of freshly injected CRs can significantly differ from the spectrum of the CR "sea". These diffuse sources are often correlated with dense molecular clouds which act as a target of the local enhanced CR injection spectrum. [11, 12] have pointed out that SNRs, the candidate CR sources *par excellence*, are located in star forming regions, which are rich in molecular hydrogen. In other words, CR sources and molecular clouds are associated and target-accelerator systems are not unusual within the Milky Way.

Successful and promising as it is [6], the idea of probing CR accelation sites with γ-ray observations is not exempt from problems. First, it is difficult to draw conclusions from observations because every observation looks different from the others. In fact, the γ-ray radiation from CR sources depends not only on the total power emitted by the sources in cosmic rays, and on the distance of the source, but also on the density of the local interstellar gas or target, on the local diffusion coefficient of the accelerated particles, and on the injection history of the source. As shown by the surveys of the Galaxy published by EGRET at MeV-GeV energies [13], by HESS at TeV energies [14] and more recently at very high energies by the Milagro Collaboration [15] the various sources differ in spectra, flux and morphology. Secondly, most of these sources especially at GeV energies lack a counterpart at other frequencies, due to the poor angular resolution obtained by the instruments at GeV energies such as EGRET. Also, the source populations at GeV and TeV energies do not seem to coincide, with few spatially coincident and spectrally compatible sources. Again, this is partly due to the poor angular resolution at GeV energies, but it might also be a consequence of the energy dependence of the physical processes involved, such as injection and diffusion. In other words it is difficult to definitely recognize the sites of cosmic ray acceleration, since very often only qualitative predictions are provided, rather than robust quantitative predictions, especially from a morphological point of view. The only way to properly model what we expect to observe is to convey in a quantitave way all information by recognizing that the enviroment, the source age, the acceleration rate and history, all play a role in the physical process of injection and all have to be taken into account for the predictions. A first step of such an investigation consists in fruitfully taking advantage of the interstellar medium data provided by the molecular hydrogen surveys in order to make robust predictions concerning the spectral and morphological features in γ-rays we expect to observe from CR sources. Hereafter we have assumed that a SNR, located at 1 kpc distance, within the region $340^{o} < l < 350^{o}$ in longitude and $-5^{o} < b < 5^{o}$ in latitude, has happened 10,100,1000 or 10000 years ago. In particular, the location of the SNR is randomly chosen to be at 342^{o} longitude and 0^{o} latitude. The gas density of the region surrounding the SNR event does not exceed $9\,\mathrm{cm}^{-3}$. The burstlike event is assumed to have injected 10^{50} ergs in cosmic rays. The CR injection spectra are assumed to be power-law with slope -2.2. The diffusion coefficient close to the SNR is $10^{28}\,(\frac{E}{10\,\mathrm{GeV}})^{1/2}\,\mathrm{cm}^2/\mathrm{s}$. The corresponding γ-ray spectra which Fermi and CTA would detect are shown in Figure 4 and 5, respectively [8]. Notably the gas enviroment where the SNR is supposed to have exploded is not particularly dense. If the same SNR event had happened in more dense region, for example 10 times more dense, it would be detectable up to about 1000 years.

CONCLUSIONS

A methodology to study the level of the cosmic ray "sea" and to unveil target-accelerator systems in the Galaxy, which makes use of the data from the high resolution survey of the Galactic molecular clouds performed with the NANTEN telescope and of the data from γ-ray instruments, has been developed. Some predictions concerning the level of the cosmic ray "sea" and the γ-ray emission close to cosmic ray sources for instruments such as Fermi and Cherenkov Telescope Array are presented.

ACKNOWLEDGMENTS

The NANTEN telescope was operated based on a mutual agreement between Nagoya University and the Carnegie Institution of Washington. We also acknowledge that the operation of NANTEN was realized by contributions from many Japanese public donators and companies. This work is financially supported in part by a Grant-in-Aid for Scientific Research from the Min-

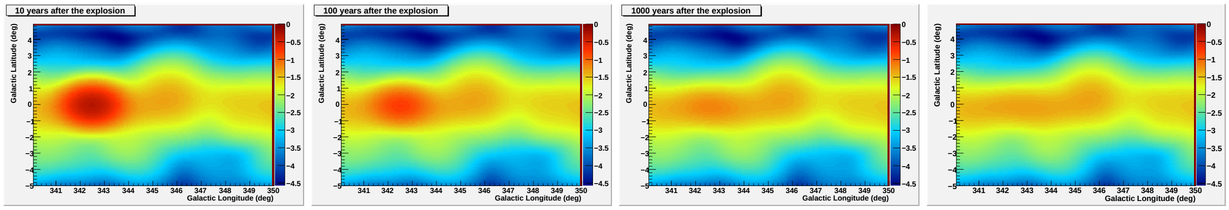

FIGURE 4. A SNR has exploded at 342^o longitude and 0^o latitude 10,100,1000 or 10000 years ago. The γ-ray spectrum which Fermi would detect at 1 GeV is expressed in $log_{10}\,\mathrm{photons}/(\mathrm{TeVcm^2srs})$. For reference Fermi point source sensitivity at 1 GeV is $2\times10^{-6}\,\mathrm{photons}/(\mathrm{TeVcm^2s})$. The γ-ray spectrum 10000 years after the SNR explosion is comparable with the γ-ray spectrum produced by the CR sea.

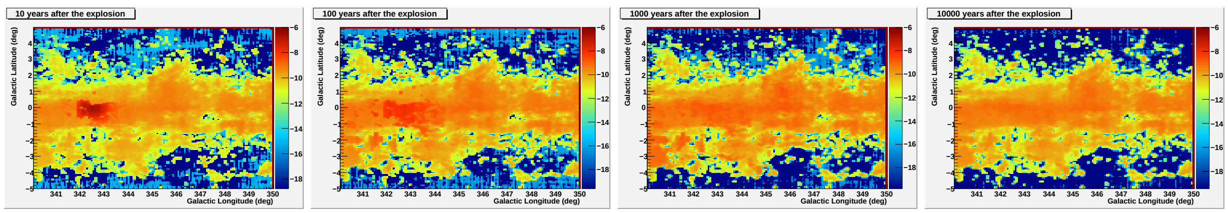

FIGURE 5. A SNR has exploded at 342^o longitude and 0^o latitude 10,100,1000,10000 years ago. The γ-ray spectrum which CTA would detect at 1 TeV is expressed in $log_{10}\,\mathrm{photons}/(\mathrm{TeVcm^2srs})$. For reference CTA sensitivity at 1 TeV is about $3\times10^{-14}\,(\frac{\theta}{PSF})\,\mathrm{photons}/(\mathrm{TeVcm^2s})$, where θ is the viewing angle and the point spread function at 1 TeV is assumed to be $PSF = 0.01^o$ [16]. The γ-ray spectrum 10000 years after the SNR explosion is comparable with the γ-ray spectrum produced by the CR sea.

istry of Education, Culture, Sports, Science and Technology of Japan (Nos. 15071203 and 18026004, and core-to-core program No. 17004) and from JSPS (Nos. 14102003, 20244014, and 18684003).

Sabrina Casanova and Stefano Gabici acknowledge the support from the European Union under Marie Curie Intra-European fellowships.

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